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# ***Multi-Mission Strategic Technology Prioritization Study***

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J.H. Smith, R. Manvi, B. Kennedy, and K. Shelton**

**"Systematic Technology Prioritization For New Space Missions"**

**Humphrey's Half Moon Inn, San Diego, CA**

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Jet Propulsion Laboratory  
California Institute of Technology  
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# Acknowledgements

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- **C. Moore, Y. Gawdiak, D. Craig, M. Hirschbein for encouragement and support in undertaking this study**
- **M. Steiner, J. Azzolini for providing data about remote observation instrument technology**
- **P. Troutman for assisting in collection of data for the OASIS reference missions, and E. Kolawa for data about extreme environments**
- **S. Prusha for assisting in selection of ECS technologies to analyze; M. Feather for providing information about correlations of tasks and needs**

# Study Staff & Roles



## ➤ JPL

- J. Derleth, Mission & Technology Portfolio Optimization
- A. Elfes, ECS Data & Analysis
- B. Kennedy, ECT Data & Analysis
- R. Manvi, Tech Life Cycle & Risk Management Model
- K. Shelton, Mission & Technology Data Base
- J. H. Smith, Integrated Risk Analysis
- G. Rodriguez, System Analysis

## ➤ **GSFC staff** (M. Steiner, J. Azzolini, J. Mapar, C. Stromgren)

# Study Objectives



- **Perform a pilot study of sufficient breadth which demonstrates in an auditable fashion how advanced space technology development can best impact future NASA missions**
  - Include wide spectrum of missions & technologies
  - Can add new missions & technologies easily
  - Optimize technology portfolios
  - Lead to rapidly prototyped example
- **Show an approach to deal effectively with inter-program analysis trades**
- **Explore the limits of these approaches and tools in terms of what can be realistically achieved (scope, detail, schedule, etc.)**

# Technology Portfolio Optimization Approach

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- **Collect performance data for many individual technologies; each data input is viewed as a statistical sample representing an expert assessment**
- **Group the technological data into a tree-like hierarchical model to predict “integrated” system, mission, and multi-mission impact of individual technologies**
- **Search computationally for technology portfolios with optimal science return, risk and cost impact**
- **Investigate sensitivity of the optimal portfolio to changes in available budget levels**

# Major Study Challenges



- Reference Missions: assess mission value; characterize capability requirements
- Technology Projections: characterize performance; manage widely dispersed and non-uniform data
- Uncertainty: incorporate & manage widespread uncertainty
- ROI Measures: formulate suitable value function for portfolio analysis
- Layers of Abstraction: choose and maintain appropriate level of analytical abstraction
- Technological Boundaries: boundaries of technology domains not clearly marked
- Many Scales: large differences in cost and performance scales for different technologies
- Performance Parameters: not fully understood for some technologies
- .....

# Implementation Approach

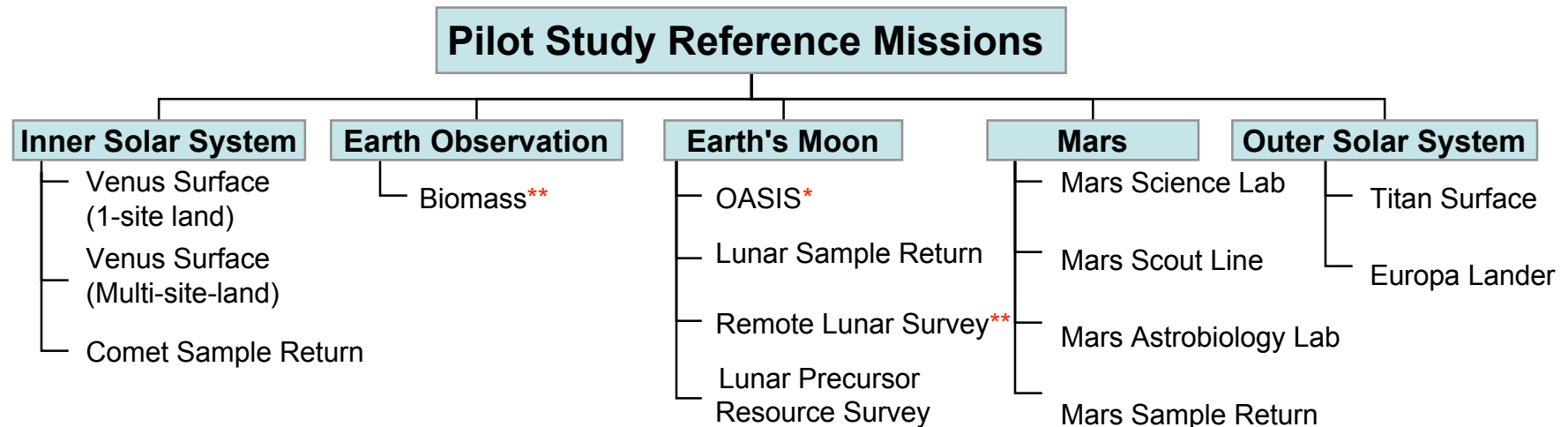


- **Iterative in three phases (keep eye on big picture early, and continuously)**
  - Phase 1 minimalist multi-mission set; ECT/ECS technologies
  - Phase 2 more extensive set of missions & technologies (June 04)
  - Phase 3 completion of full study (December 04)
  
- **Maintain high degree of connectivity**
  - Space Architect
  - Revolutionary Mission Concepts
  - Advanced Space Technology Programs
  - Enterprises
  - Centers
  - Etc.

# Pilot Study Reference Missions



(Organized by Science-Site Location)



- Initial reference mission set as of April 15, 2004
- More missions and enabling technologies will be added throughout the period of performance of the study

\* OASIS is a near Earth transportation infrastructure that enables access to the Moon. It consists of: a Hybrid Propellant Module, a Chemical Propulsion Module, a Solar Electric Propulsion Module, and a Crew Transport Vehicle.

\*\* GSFC contribution to this study focuses on these missions



# Reference Missions & Major Challenges

## (Minimalist Mission Set for PHASE I)



Reference Mission Classes (not listed in order of priority)	Major Challenges
<b>Earth's Moon:</b> Orbital Aggregation and Space Infrastructure Systems (OASIS); Lunar Remote Survey; Lunar Surface Missions; etc.	Deep Space Robotic Rendezvous & Docking; Long Term Cryogenic Fuel Storage in Space (>2 years); Long Life Ion Engines(>15 K-hours)
<b>Mars Surface:</b> (e.g. Mars Science Laboratory; Astrobiology Field Lab; Mars Sample Return; etc.)	Long-Range, Long-Life Mobility (10's of kilometers, >600 sols); Substantive Sample Collection and Return (>1kg, 0<depth<100m subsurface)
<b>Earth Observation:</b> Biomass	Lidar/Radar Instrument Systems; Multi-Spectral Scanner; Sensor Webs & Data Fusion
<b>Outer Solar System:</b> Titan Surface; Europa Lander	Extreme Environments; Sub-Surface Ice Mobility
<b>Inner Solar System:</b> Venus surface; comet sample return	Extreme Environments (460C temp; 90 bar pressure; sulfuric acid clouds at 50 km)

### ➤ Technologies to be evaluated will include:

- Technological products in several discipline fields (aimed at operational flight system implementation (e.g. advanced materials, structures, etc.))
- Risk assessment tools and infrastructure to allow for risk quantification, and risk mitigation during an entire mission life-cycle, but that do not necessarily appear in the flight system implementation (e.g. risk management methods)

# Enabling Technologies for Which Data Has Been Collected to Date



- **Extreme Temp & Pressure Components, Thermal Control, Pressure-Vessel-Encapsulated Electronics (Venus)**
- **Electric & Chemical Propulsion; Reaction Control; Multifunction Structures; Fuel Storage & Control; Syntactic Foams, Formation Flying (OASIS)**
- **Entry Descent & Landing; Surface, Aerial, Subsurface Mobility; Manipulation, Drilling, Sampling (Mars, Titan, Comet, Lunar Surface)**
- **In-Space Inspection, Maintenance, Assembly (OASIS, Large Observatory Platform, Gateway, Space Solar Power)**
- **Risk Methods, Tools and Workstation; Mishap Anomaly Data Base; Complex Systems Research; Risk Characterization & Visualization; etc. (All Reference Missions)**

# Enabling Technology Areas

(for which data has been collected to date)



Enabling Technology Areas	Missions
Electric & Chemical Propulsion; Reaction Control; Multifunction Structures; Fuel Storage & Control; Syntactic Foams, Formation Flying; In-Space Robotic Inspection, Maintenance, Assembly	OASIS
Entry Descent & Landing; Surface, Aerial, Subsurface Mobility; Manipulation, Drilling, Sampling	Mars, Earth's Moon, Titan, Comet
Risk Methods, Tools & Workstation; Mishap Anomaly Data Base; Complex Systems Research; Risk Characterization & Visualization; etc.	All
Extreme Temp & Pressure Components, Thermal Control, Pressure-Vessel-Encapsulated Electronics	Venus, Titan, Europa

# Technology Areas are Decomposed into Many Sub-Areas & Performance Parameters



A Few Typical Technology Areas	A Few Typical Technology Sub-Areas	A Few Typical Performance Parameters
Multi-Function Structures	Modular, Distributed Structures, Deployable Structures, etc.	Contract/Extend (cm), Power per Mass (W/kg), etc.
Fuel Storage & Control	On Orbit Cryogenic Fuel Transfer, Tank Pressure Control, Fuel Storage, etc.	Flow Rate (kg/min), Pressure (kPa), Time (yrs), etc.
Subsurface Ice Mobility	Range, Radiation Dose, Payload Capacity, Ambient Pressure, etc.	Distance (km, mRads), Mass (kg), Pressure (atm), etc.
Extreme Temperature & Pressure Components	High Temperature Electronics, Permanent Magnets, Energy Storage, etc.	Temperature (Celsius), Pressure (Bars), Energy Density (Whr/l) etc.
Risk Methods, Tools & Workstation	Model Based Risk Analysis, Mission Risk Profiling Capability, etc.	Accessibility, applicability to multiple mission phases, risk mitigation coverage

# Mission & Technology Data Base



Mission Parameters	level	metric	unit	polarity	SOA		Venus Surface Mission I							Venus Surface Mission II						
					SOA	TRL	need	mean	worst	best	TRL	Yrs	\$M	need	mean	worst	best	TRL	Yrs	\$M
Operational Lifetime	0	# Yrs Survival	#	+	0.5	3	2						N/A							
Number of Landing Sites	0	# Landing Sites	#	+	1	1	1						N/A							
Number of Samples per Site	0	# Samples Per Site	#	+	1	3	5						N/A							
Projected # of Years to Phase A	0	Years	#	-	N/A	N/A	8	8	10	5	N/A	N/A	N/A	15	15	20	10	N/A	N/A	N/A
Technology	level	metric	unit	polarity	value	TRL	need	mean	worst	best	TRL	Yrs	\$M	need	mean	worst	best	TRL	Yrs	\$M
Extreme Temp & Pressure Components (460C/90bar)	1																			
Sensors Operating at High Temp/Pressure	2																			
Temperature Sensors	3												5							5
	4	Operating Temperature	degree Celsius	+	460	3	460	480	460	500	5	2.5		460	480	460	500	6	5	1
	4	Operating Pressure	bar	+	90	3	90	120	80	150	5	1.5		90	120	80	150	6	5	1
Pressure Sensors	3												5							
	4	Operating Temperature	degree Celsius	+										480	460	500	6	5	1	
	4	Operating Pressure	bar	+										460	450	470	6	5	1	
Position Sensors	3												5							
Position Sensors-Distance	4																			
	5	Operating Temperature	degree Celsius	+	600	3	460	460	450	460		1.25		460	460	450	460	6	5	1
	5	Operating Pressure	bar	+	1	3	90	90	80	100		5	1.25	90	90	80	100	6	5	1
Position Sensors	4																			
	5	Operating Temperature	degree Celsius	+	350	3	460	460	450	470	6	5	1.25	460	460	450	470	6	5	1
	5	Operating Pressure	bar	+	1	3	90	90	80	100	6	5	1.25	90	90	80	100	6	5	1
High Temperature Sensors (CMOS)																				
		Operating Temperature	degree Celsius	+										460	460	450	470	6	5	1
		Operating Pressure	bar	+										90	90	80	100	6	5	1
Multi-Sensor Interfacing																				
		# Sensors Integrated	#	+										4	4	3	5	6	5	2
Sample Acquisition Systems																				
Actuators Operating at High Temp/Pressure																				
		Operating Temperature	degree Celsius	+										500	500	480	510	6	5	1
		Operating Pressure	bar	+										90	90	80	100	6	5	1
High-Temperature Actuators (CMOS)																				
		Operating Temperature	degree Celsius	+										460	460	450	470	6	5	1
		Operating Pressure	bar	+										90	90	80	100	6	5	1
Permanent Magnets																				
		Max Energy Product	Whr/kg	+										26	26	18	32	6	5	1
		Coercivity	A/m	+										10000	10000	8000	12000	6	5	1
		Max Operating Temperature	degree Celsius	+										460	460	450	470	6	5	1
Energy Storage																				
High Temperature Batteries (Rechargeable)																				
		Energy Density	Whr/kg	+										200	200	150	250	6	5	2
		Operating Temperature	degree Celsius	+										460	460	450	470	6	5	2
		Shelf Lifetime	Yrs	+										5	5	4	6	6	5	1
High Temperature Batteries (Non-Rechargeable)																				
		Energy Density	Whr/kg	+										200	200	180	220	6	5	1
		Operating Temperature	degree Celsius	+										460	460	450	470	6	5	1
		Shelf Lifetime	Yrs	+										5	5	4	6	6	5	1
		# of Recharge Cycles	#	+										100	100	80	120	6	5	1
Na/NiCl2 Rechargeable Batteries																				
		Energy Density	Whr/kg	+										200	200	180	220	6	5	1
		Operating Temperature	degree Celsius	+										460	460	450	470	6	5	1
		Shelf Lifetime	Yrs	+										5	5	4	6	6	5	1
		# of Recharge Cycles	#	+										100	100	80	120	6	5	1

This is an early draft for April 15<sup>th</sup>, 2004. Please do not distribute.

# Mission & Technology Data Base

## --Current Size Summary--



- **Size of Mission & Technology Capability Data Base (as of April 15, 2004)**
  - 13 missions covering wide spectrum of NASA strategic plans
  - 23 technology areas (structures, energetics, extreme environments, surface mobility, etc.)
  - 86 technology sub-areas (batteries, payload capacity, thermal control, etc.)
  - 167 technological performance parameters (power density, operating temperature, etc.)
- **Remarks About Data Base**
  - Current data set is more detailed in some areas than in others
  - More technologies & detail will be collected in subsequent phases
  - Our analysis methods can handle data sets with non-uniform detail

# Risk Related Requirements



(from Point of View of a Project Manager)

## ➤ Risk Management Must:

- Delineate major risks: Technical, Human, Organizational, Budgetary, and Schedules ;estimate and rank risk levels
- Provide ways to visualize risk elements, time profile, and mitigation strategies
- Assure that the systems and trade analysis includes cost, performance, and risk
- Provide auditable benefit/cost of implementing begin-to-end risk mitigation strategies

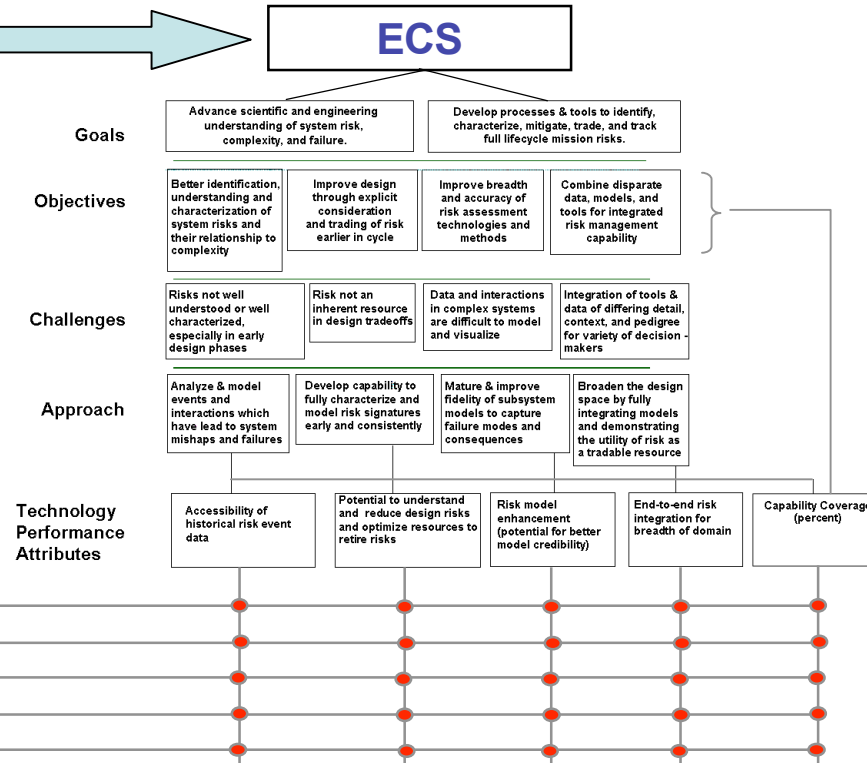
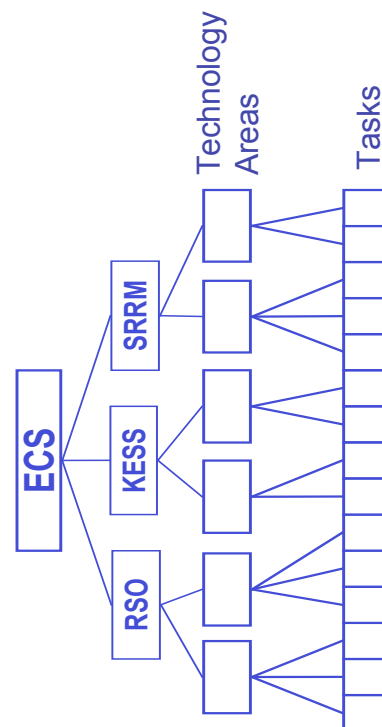
# Connecting Risk Technologies to Requirements

Requirements:



**ECS**

- ❑ Delineate major risks: Technical, Human, Organizational, Budgetary, and Schedules; estimate and rank risk levels
- ❑ Provide ways to visualize risk elements, time profile, and mitigation strategies
- ❑ Assure that a substantial portion of the design space is explored including cost, performance, and risk
- ❑ Provide auditable benefit/cost of implementing end to end risk mitigation strategies



•ECS: Engineering of Complex Systems

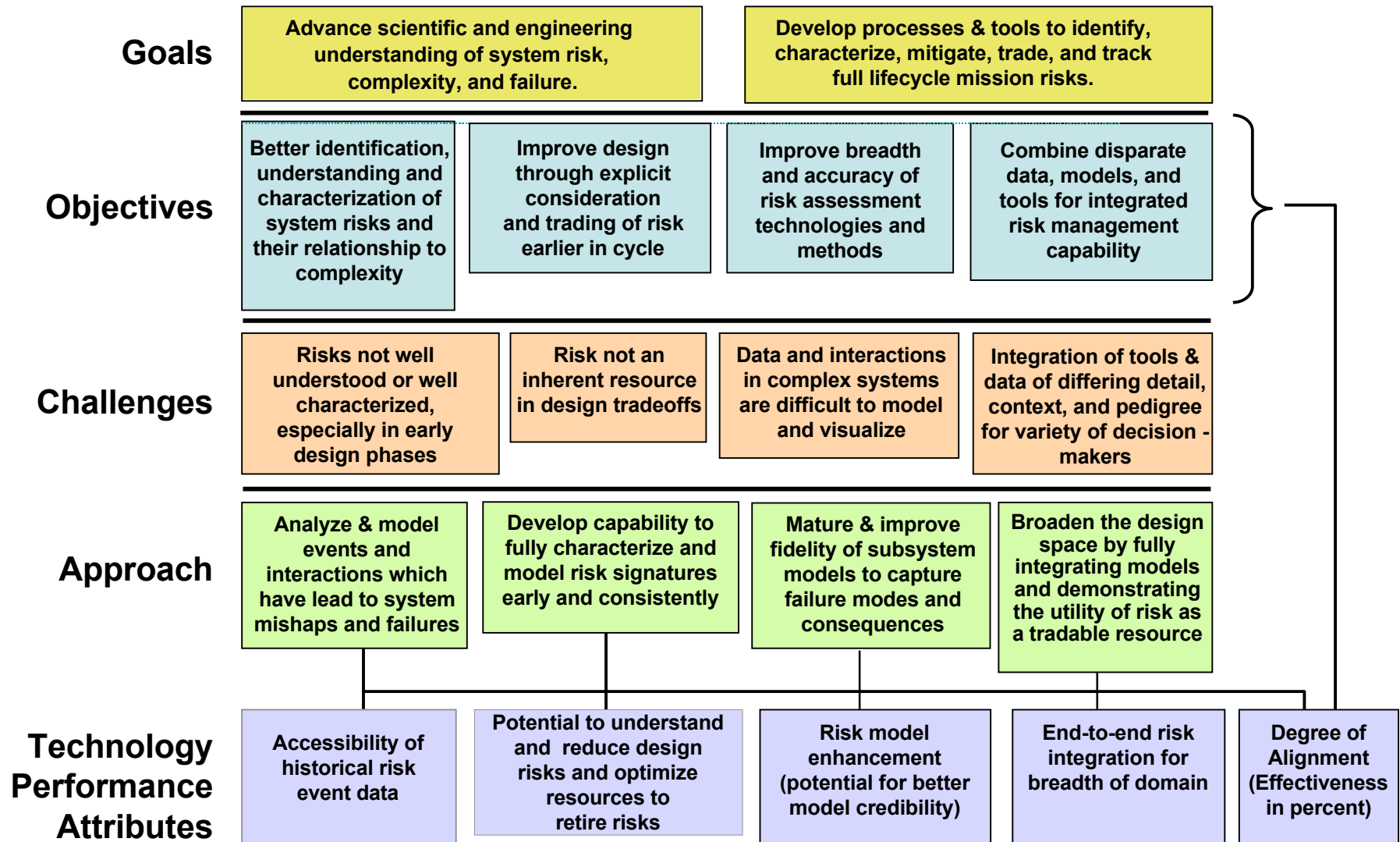
➤SRRM: System Reasoning and Risk Management

•KESS: Knowledge Engineering for Safety and Success

•RSO: Resilient Systems and Operations

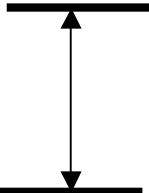
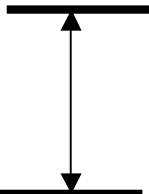
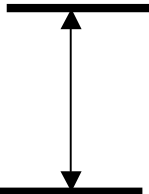
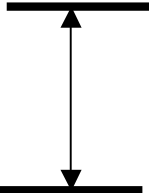


# System Reasoning and Risk Management (SRRM) Project Executive Summary



# Attribute Definitions



<b>Accessibility of risk data</b>	<p>Best Case</p>  <p>Worst Case</p>	<p>10</p> <p>5</p> <p>0</p>	<p>Easy to use DB spans multiple mission/projects with risk events categorized for search.</p> <p>DB may be limited to specific category or series of missions.</p> <p>Supporting data/verifications are anecdotal (narrative) format without categories of risk events for easy search. May require further processing to another format.</p>
<b>Potential to reduce design risks</b>	<p>Best Case</p>  <p>Worst Case</p>	<p>10</p> <p>5</p> <p>0</p>	<p>Technology helps to identify and reduce risks during early phases of project (Phase A/B) with potential to dramatically reduce overall project costs by reducing rework.</p> <p>Technology helps identify/reduce mission risks for Phase C/D; Large potential cost benefits if used. Provides a screen that limits potential risks from passing CDR.</p> <p>Technology helps identify technology development or subsystem risks, but may or may not influence overall system risk.</p>
<b>Risk model enhancement</b>	<p>Best Case</p>  <p>Worst Case</p>	<p>10</p> <p>5</p> <p>0</p>	<p>Technology provides new approach for addressing design risk life-cycle or part of life-cycle not previously addressed (e.g., mgmt, org. risks)</p> <p>Technology either provides new, more effective approach for risk analysis or fills missing gap in temporal or breadth of risk analyses (but not both)</p> <p>Technology does not address missing gap in design life-cycle.</p>
<b>End-to-end risk integration</b>	<p>Best Case</p>  <p>Worst Case</p>	<p>10</p> <p>5</p> <p>0</p>	<p>Technology provides synergistic integration with other tools and databases fully compatible with emerging design environments (temporal and breadth).</p> <p>Risk technology allows interaction with common databases but cannot be integrated with other stand-alone applications.</p> <p>Technology is stand-alone; focused, narrow; little breadth or temporal range, databases are separated with little or no connectivity. Integration difficult.</p>

# All SRRM Technology Areas Are Included for the Pilot Study

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1. Risk Methods/Tools (RMT)
2. Risk Workstation (RWS)
3. Mishap/Anomaly Database (MAIS)
4. Model-Based Hazard Analysis (MBHA)
5. System Complex Research (SCR)
6. Risk Characterization/Visualization (RCV)
7. Risk-Based Design (RBDO)
8. Data Mining Research (DMR)
9. Investigation Methods/Tools (IMT)

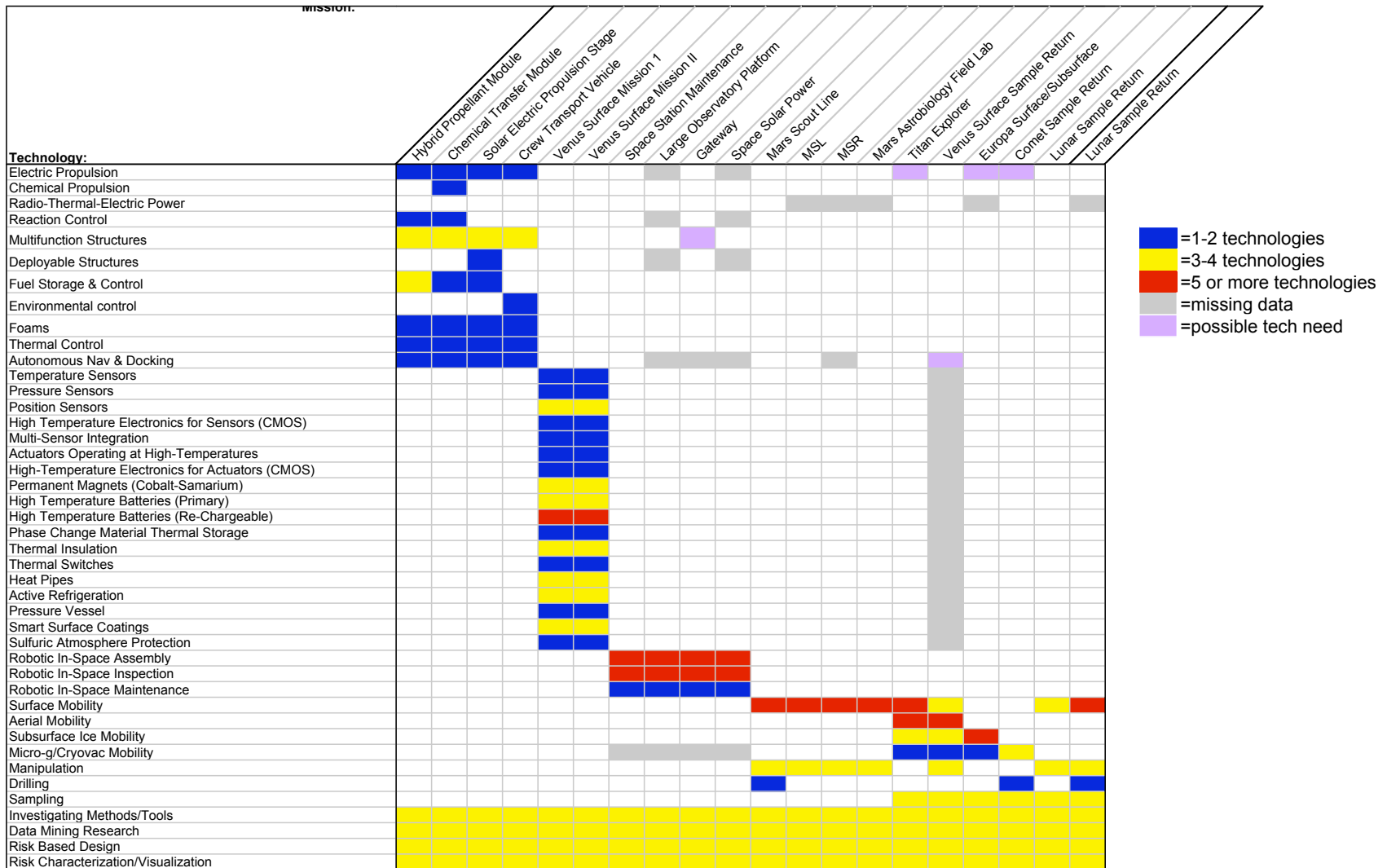
# Typical SRRM Technology Area Data\*



Technology	Level	Metric	Unit	Polarity	SOA	Low	ML	High	\$M
		How performance is measured	What unit performance is measured in	+ = Better if performance is higher - = Better if performance is lower	Current state-of-the-art for similar technologies	Technologist's estimate of low, most likely, and high values of what will be provided to the mission			How much the technologist needs to achieve TRL 6 in \$M
ECS	1								
SRRM	2								
RISK Methods & Tools	4	Accessibility of Historical Risk Event Data	0-10	+	4	7	8	9	2
		Potential to Understand and Reduce Design Risks and Optimize Resources to Retire Risk	0-10	+	1	7	8	9	
		Risk Model Enhancement (Potential for Better Model Credibility)	0-10	+	2	9	10	10	
		End-to-end Risk Integration for Breadth of Domain	0-10	+	2	8	9	10	
		Extent of Needs Covered	0-1	+	0.5	0.7	0.8	0.9	

\*SRRM data cast in same format used for all other technologies (shown in slide 14) 20

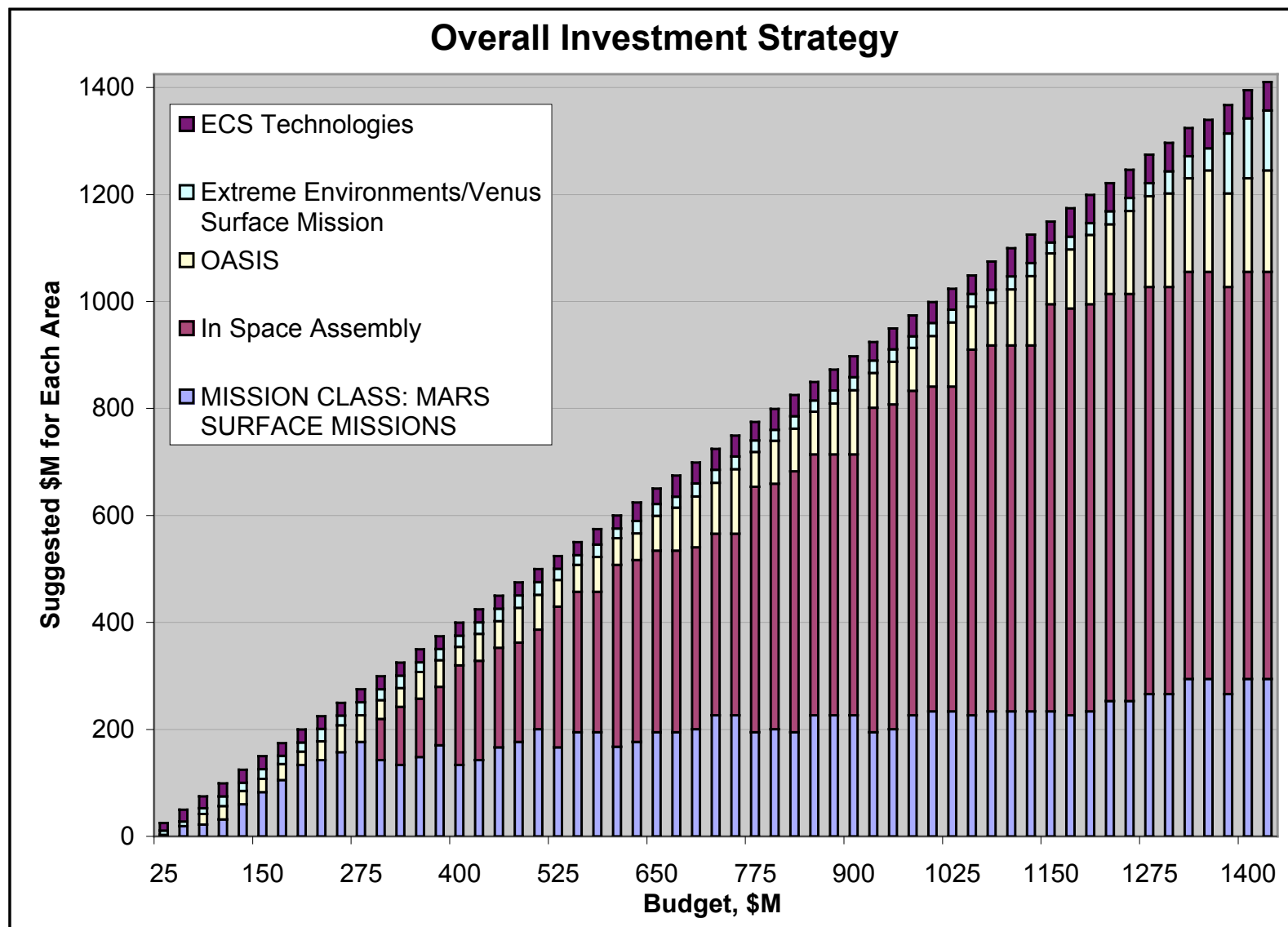
# Mission-Technology Complexity Map

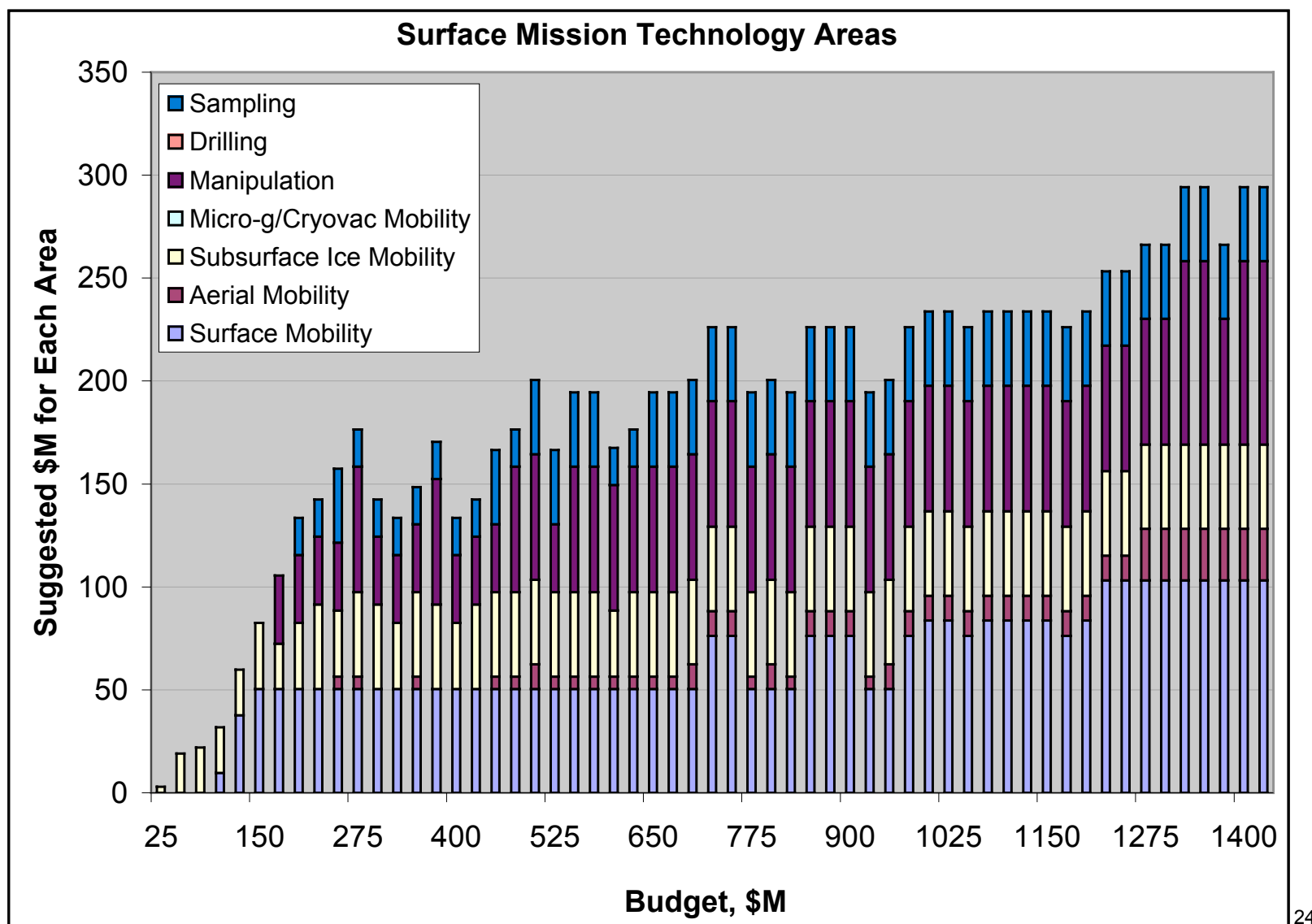


# Analysis Options Used to Get Typical Results in Slides 25-30

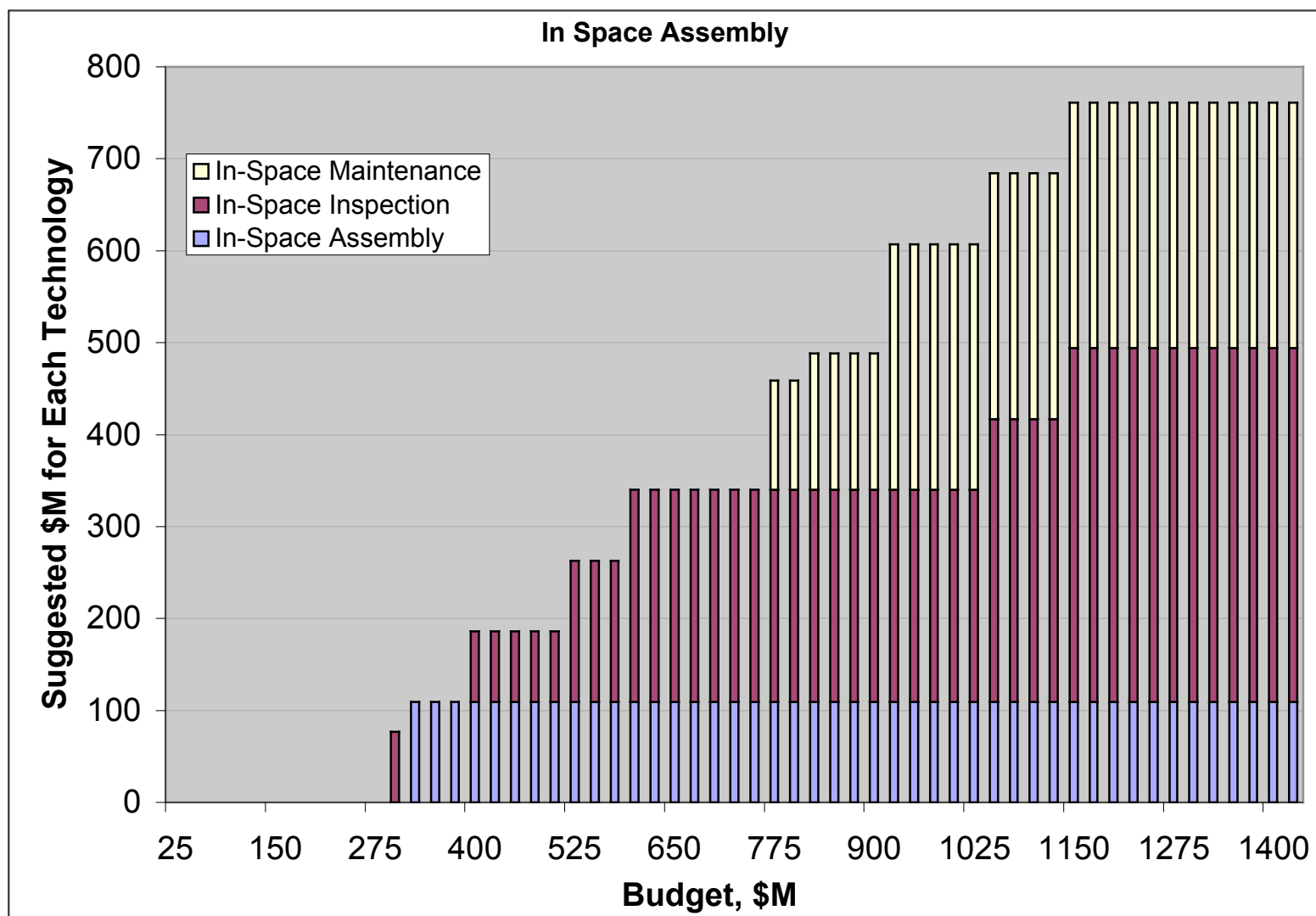


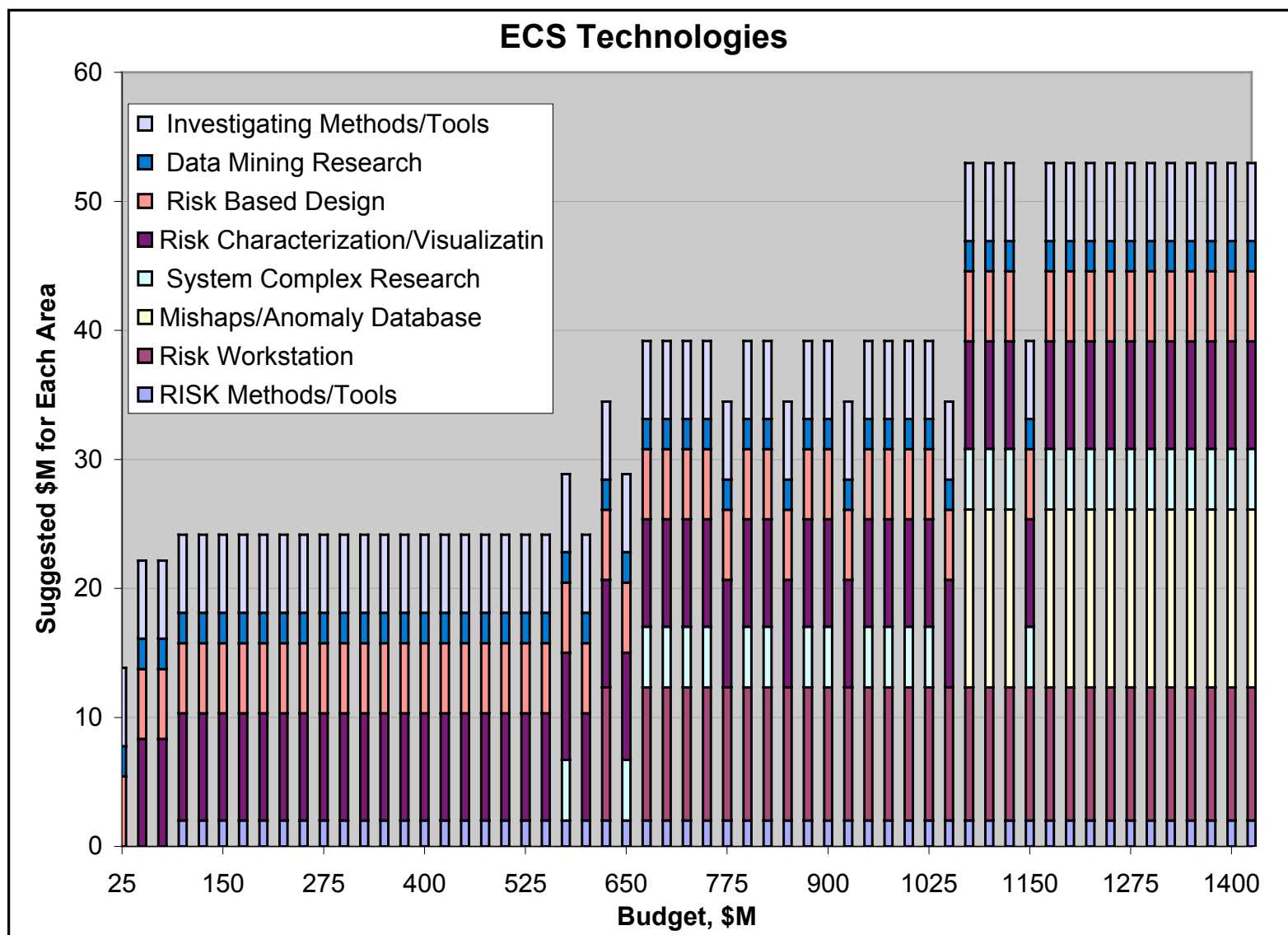
Analysis Options Used	Other Options Available
Uniform science-return value for all missions	Can assign non-uniform science return value (user prescribed)
Uniform value for all technologies at the same hierarchical level; “democratic” hierarchy	Can prescribe general technology organizations; based for example on mission and system decomposition
Technology correlations and co-dependencies set to zero	Can explicitly include correlation & co-dependency parameters when available
Risk estimates based only on performance uncertainty	Can include cost, schedule and other risk factors
Identical development time (~10 yrs) for all technologies	Can vary technology development time as a model parameter
TRL data not included in technology projections	Can analyze TRL data within existing analysis framework

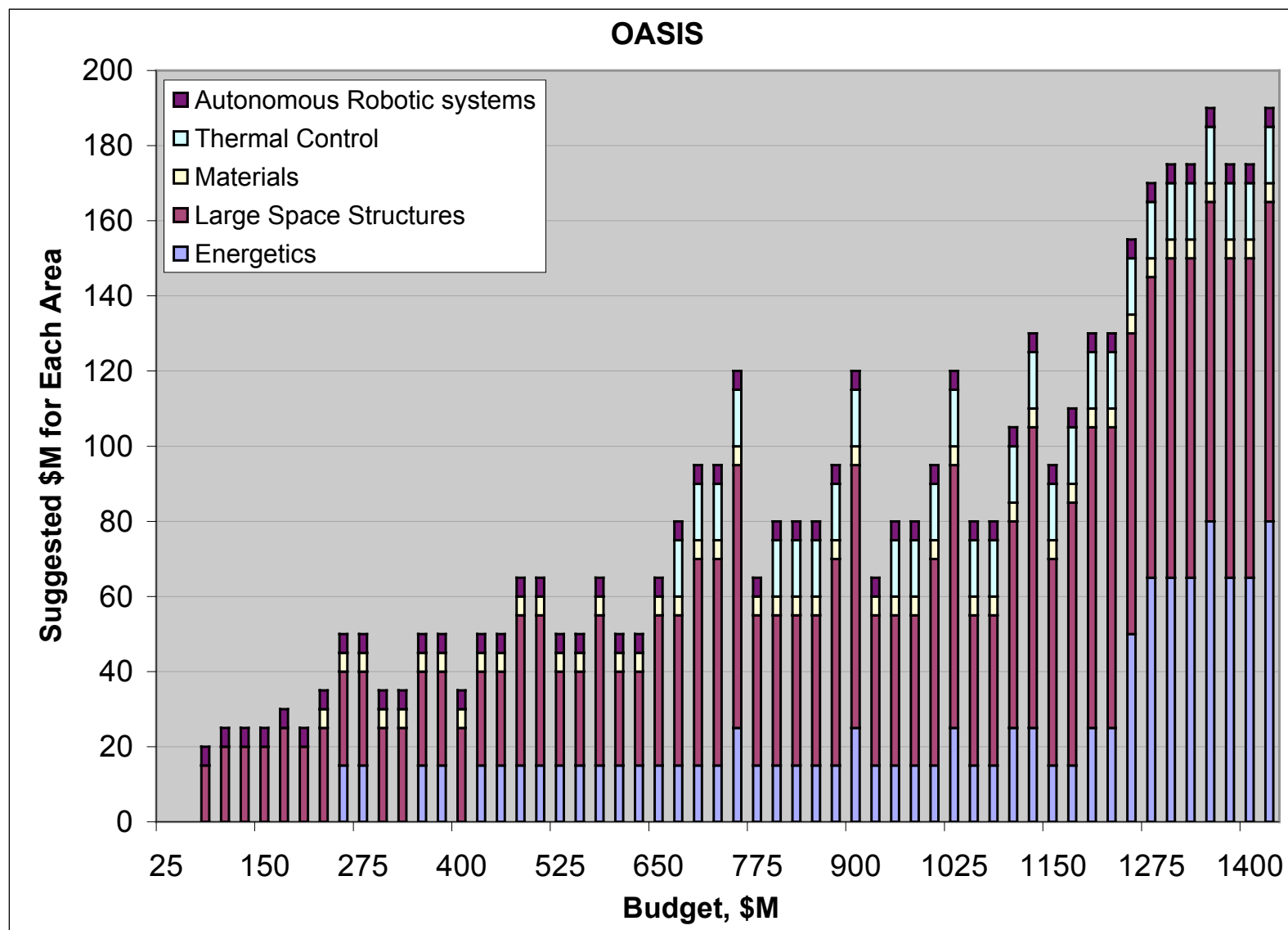


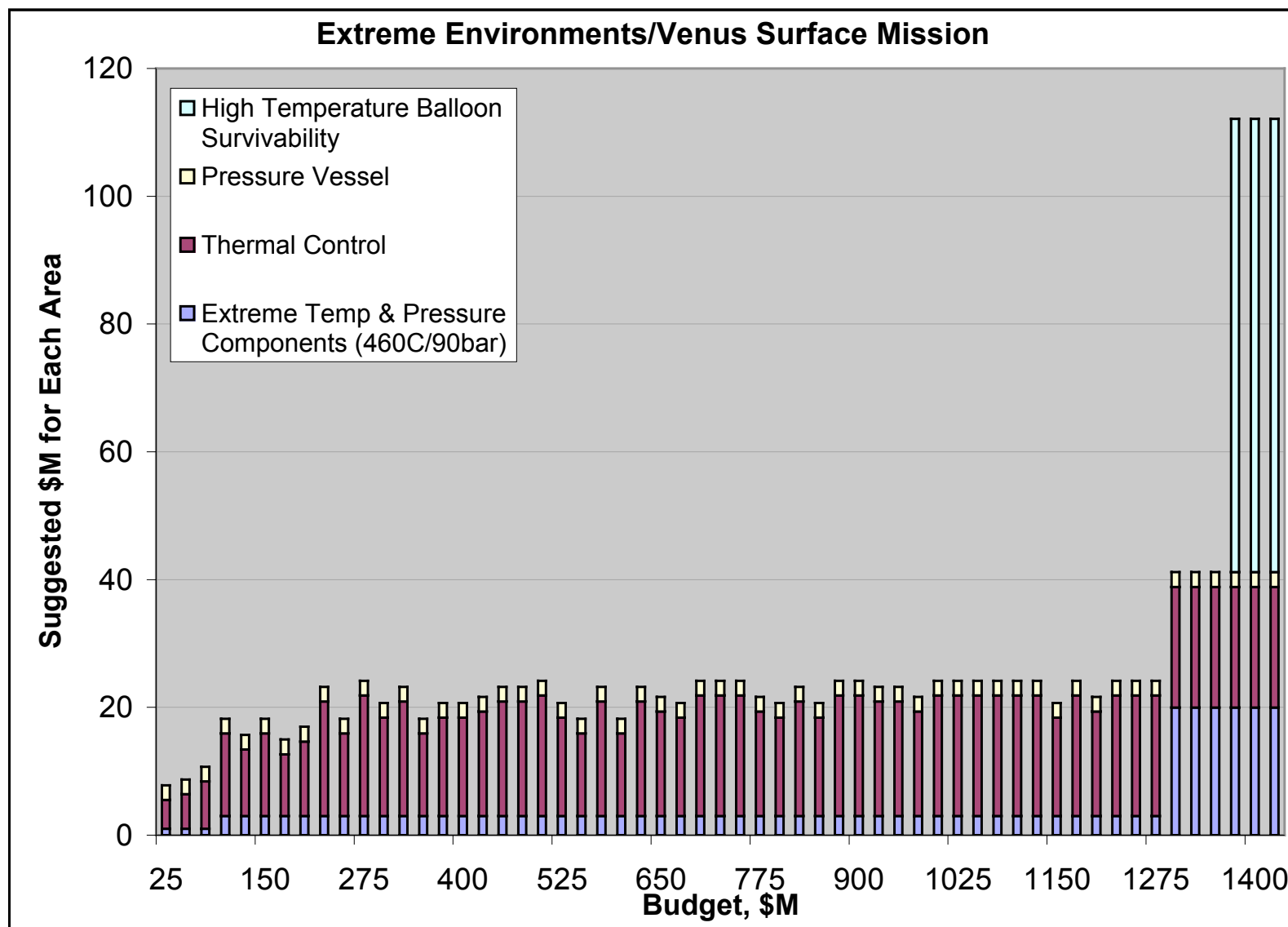


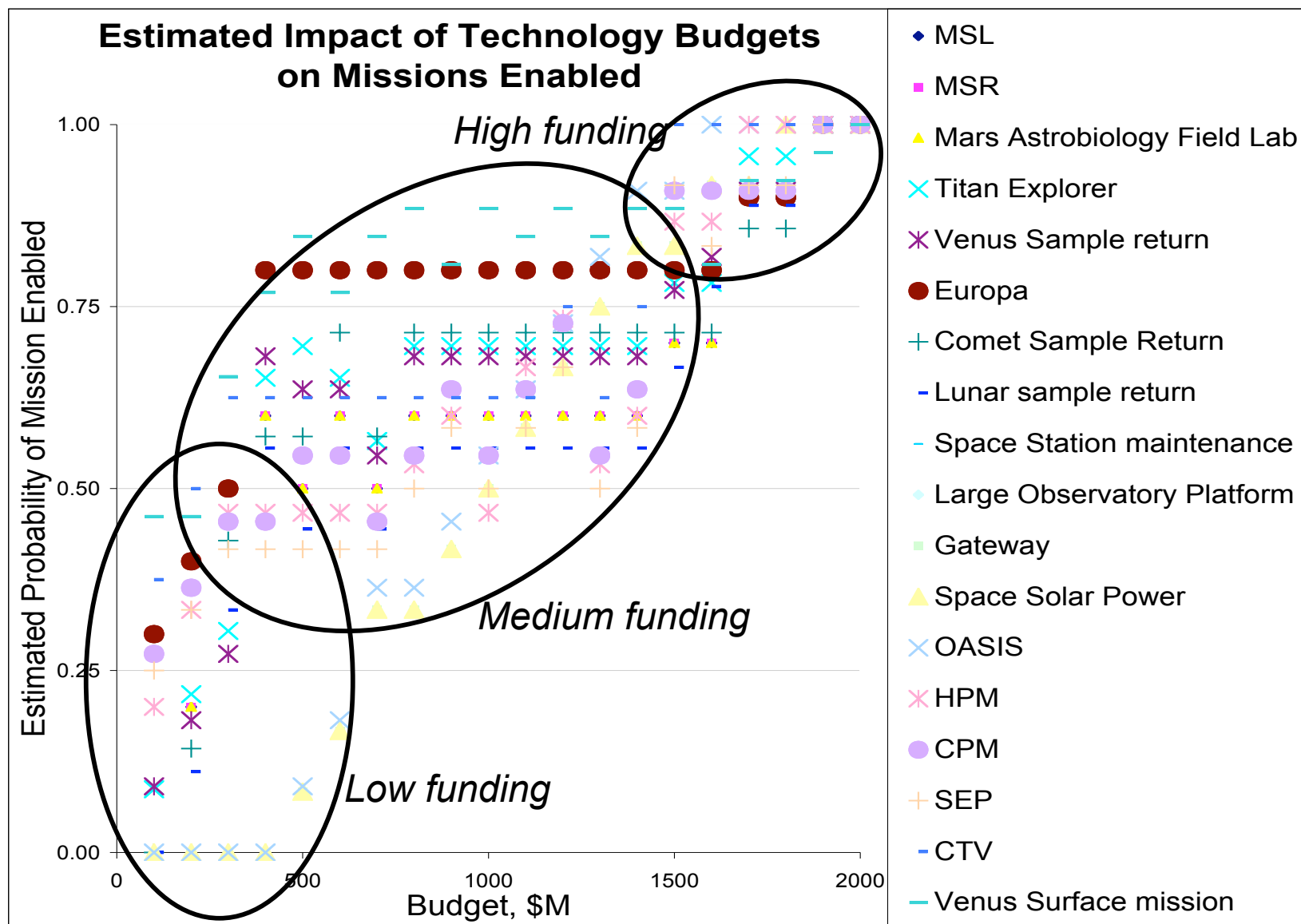




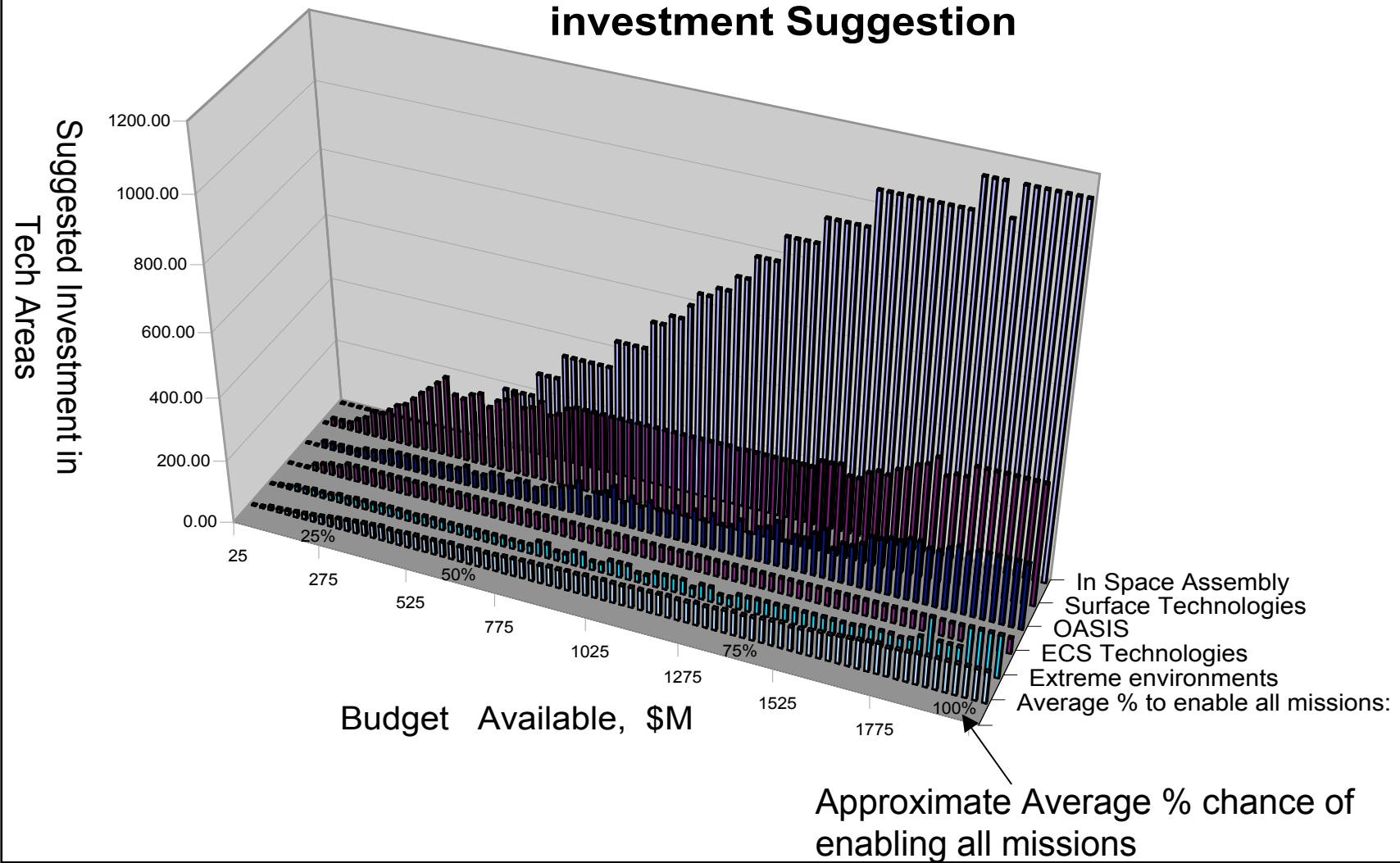








## Combined est. Mission Success % and Tech Area investment Suggestion



# Concluding Remarks



## ➤ Study Results to Date (January-March, 2004)

- Initial data base for 13 missions and 167 technology performance parameters in 23 technical areas, representing Code T,S,M,Y enterprises
- Rapidly prototyped analysis capability to evaluate impact of technological investment on science and exploration return

## ➤ Work Remaining (April-December, 2004)

- Expand data base to include more enabling missions and technologies (e.g. modular distributed structures, etc.)
- Conduct more in-depth analysis of the representation and fidelity of the existing data set, and a more detailed treatment of the consistency and integration across program elements
- Calibrate data base and analysis with extensive WHAT-IF computational